BELLCOMM, INC.

SUBJECT: A Description of the S-IC Stage Propellant and Propellant Pressurization Systems - Case 330

DATE: April 20, 1967

FROM: S. H. Levine

ABSTRACT

The purpose of this memorandum is to provide a technical description of the S-IC stage propellant storage, delivery and pressurization systems in sufficient detail such that the user of this information can be better equipped to understand and assess the impact and significance of changes as they occur to the S-IC stage in these areas.

The information and data contained herein has been compiled from various Boeing Company and MSFC documentation which includes design requirements documents, end item specifications and other documentation and data sources.

(NASA-CR-153830) A DESCRIPTION OF THE S-IC STAGE PROPELLANT AND PROPELLANT PRESSURIZATION SYSTEMS (Bellcomm, Inc.) 21 p

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MEMORANDUM FOR FILE

The purpose of this memorandum is to describe the S-IC Stage propellant storage, delivery and pressurization systems in sufficient detail such that the user of this information will be better equipped to understand and assess the impact and significance of changes which occur to the S-IC Stage in these areas.

1. LOX Systems (Figure 1)

   a. LOX Loading and Draining LOX is loaded (Reference 1) on the S-IC Stage from a 900,000 gallon ground supply tank by launch area GSE. The loading sequence is as follows:

      1. At about T-6.5 hours in the countdown LOX commences to flow at a throttleable rate of 300 gpm. This initial flow is used to precool S-IC cryogenic hardware to temperatures suitable for LOX storage and delivery functions.

      2. LOX is then pumped to the LOX tank at the "slow fill rate," approximately 1,500 gpm, until a stable liquid level is reached at which oxidizer "geysering" (see explanation below) is eliminated (about 5% of tank volume).

      3. A "fast fill rate," 10,000 gpm, is employed at this time for the main fill operation until the LOX level reaches 93% of the total LOX requirement.

      4. At this point, the "slow fill rate" is resumed to complete LOX loading at about T-5.5 hours in the countdown.

   LOX topping to compensate for boiloff prior to liftoff (estimated boiloff rate - 216 gpm) is performed at the original 300 gpm rate. Automatic LOX loading cutoff backup for the ground system is provided by a LOX level sensor at the top of the tank should the tank become inadvertently overloaded. LOX loading is controllable to an accuracy of ±.25% of the desired LOX weight.

[redacted]

The 345,000 gallon LOX tank (Reference 2) is filled through two six-inch diameter fill and drain lines, each containing a ground controlled fill and drain valve (with a valve actuator heater). These lines are connected between the Intertank Umbilical interface of the stage structure and the fill and drain fitting on the LOX tank aft bulkhead.

During LOX filling, the LOX vent valve and the LOX vent and relief valve (to be discussed later) are held in an open position while the ullage area is purged by ground supplied gaseous nitrogen.

LOX draining, if required, is accomplished at a rate of about 7,480 gpm via the fill and drain lines previously mentioned and a six-inch suction line drain which is connected from the inboard LOX suction line (above the LOX prevalve in the Thrust Structure) to the Aft Umbilical Plate #1 interface. The LOX vent valve and the vent and relief valve are kept closed and the tank is pressurized during drainage. This is done to prevent tank collapse and to establish an adequate pressure differential with the ground storage tank. Pressure relief is provided should the tank become overpressurized. A supplementary emergency drain line, which includes a drain valve, is connected to the LOX tank aft bulkhead during static testing only. This enables drainage of the LOX system at an accelerated rate (18 minutes).

b. <u>LOX Measurements</u> Two capacitive type continuous level topping sensors located at the top of the S-IC LOX tank provide LOX level data to the LCC during LOX loading. These sensors provide LOX liquid level data for levels above the 3% ullage level in the tank and are designed to overlap with the LOX liquid level measuring system of the S-IC stage.

The LOX liquid level and slosh measurement system consists of four continuous level variable capacitance type balanced bridge probes which are located near the LOX tank wall at 90° intervals. These sensors provide LOX level data for levels below levels monitored by the continuous level topping sensors described above.

c. LOX Conditioning An undesirable by-product of LOX boiloff is "geysering" in LOX suction lines and in the LOX tank prior to launch. Geysering is a phenomena (Reference 7) whereby as the cryogenic liquid warms and the LOX saturation temperature is reached, GOX bubbles form in the LOX suction lines. As the bubbles rise to the surface of the cryogenic liquid, the bubble volume increases. Upon approaching the surface, the bubbles force the cryogenic liquid above the bubbles to break away from the liquid surface ("geyser"). Liquid which has broken away returns to the surface creating a pressure surge in the lines. It is possible for pressure surges (i.e., transient loads) of the magnitude created by geysering to cause structural damage of catastrophic proportion. In addition to the above, geysering is accompanied by temperature (i.e., density) variations and stratification in the lines. Excessive density variation at pump inlets can adversely affect the engine start process.

A LOX conditioning system employing induced helium bubbling and thermal pumping techniques is used to prevent the above problems by providing better thermal circulation. LOX bubbling is initiated by introducing ground supplied gaseous helium into LOX suction lines #1 and #3 (Figure 1) at a flow rate of 500 scfm (at -250°F). As the helium bubbles rise, thermal energy is liberated from the LOX in these lines and thermal convection currents are created in the upward direction. Interconnect lines containing flow control interconnect valves connect outboard suction lines to one another below the LOX prevalves and link outboard suction lines to the inboard suction line above its prevalve. Interconnect lines provide the mechanics for completing thermal convection paths from line #2 and lines #4 and #5 to the cooled LOX suction lines, #1 and #3 respectively, where bubbling is taking place. Helium bubbling is normally terminated when LOX reaches about the 5% level during loading and is resumed at T-10 minutes in the countdown to ensure that suction lines are below the LOX saturation temperature. LOX bubbling is completed at T-71 seconds in the countdown, and interconnect line flow is subsequently prohibited. At this point, thermal pumping has been terminated.

d. <u>LOX Pressurization</u> (Figure 2 and Table 2) LOX tank pressurization is required to ensure proper engine turbopump pressure during engine start, thrust build-up and flight. The MSFC <u>minimum</u> steady state LOX pump net positive suction head (NPSH) requirement on the S-IC stage is 81 feet of LOX (39.8 psia). This value is some 25% above the engine manufacturer's stated requirement (65 feet).

Preflight pressurization, "prepressurization," which commences after helium bubbling is completed, is accomplished by supplying GSE gaseous helium, via umbilical, to the GOX distributor located in the forward bulkhead of the LOX tank. Prepressurization is monitored by a pressure switch, located in the LOX tank forward bulkhead, which controls the position of the ground pressurant supply valve (GSE), the LOX vent valve and the LOX vent and relief valve. The maximum prelaunch ullage pressure is 26 psia. Prepressurization, which takes about 45 seconds, is performed with vent and vent and relief valves closed and is maintained until liftoff.

Inflight pressurization is performed after engine ignition by bleeding a small amount of LOX from the high pressure side of the engine turbopump, at the main LOX valve, through the engine heat exchanger (Figure 3) where engine turbine exhaust heat converts it to GOX. GOX flows from each engine heat exchanger into a common manifold which contains a GOX flow control valve. This valve regulates GOX flow to the LOX tank (between 20 and 40 lbs/sec) and maintains a ullage pressure in the tank of between 18 and 20 psia by means of a tank pressure sensing feedback line to the valve. GOX flows from the flow control valve into the GOX distributor at the forward apex of the LOX tank and then into the ullage area of the tank. The inflight pressurization system is nominally designed for no GOX venting during flight, however, should overpressurization occur, pressure venting by vent valving is electrically initiated by pressure switches (2) mounted in the LOX tank dome. One switch is designed to open the LOX vent valve at pressures of 27.5 to 29.0 psia until T+65 seconds of flight, while the other is designed to open the LOX vent and relief valve at pressures of 23.7 to 25.5 psig after T+75 seconds of flight. Venting by either pressure switch (i.e. valve) may occur between T+65 and T+75 seconds of flight. In the event of pressure switch or solenoid control failure, the vent and relief valve is designed to mechanically relieve the LOX tank at pressures in excess of 24.0 psig.

e. LOX Delivery LOX is delivered to the engines at a rate of approximately 3950 lbs/sec (per engine) by way of five 17-inch diameter LOX suction lines (Reference 2). These lines (Figure 4) are equipped with gimbals and expansion joints to compensate for engine gimbaling motions, induced stage stresses, alignment tolerances and thermal growth. Pressure-volume compensators (PVC) are installed in the ducts at the aft end to ensure a constant flow rate regardless of engine gimbal position. Each suction line contains a normally opened, pneumatic piston-operated ball-type prevalve which is located at the fuel tank LOX tunnel outlet. Nitrogen control pressure is provided by the solenoid control valve which controls both the LOX and the fuel prevalves. LOX prevalves serve as emergency control valves which shut off LOX flow to the engine during static test, prelaunch and flight operations after sensing engine thrust decay.

Each suction line contains a LOX depletion sensor (having redundant sensing elements) which is capable of determining the LOX level in the emptying LOX system to within ±0.4 inches when the LOX level in the lines is decreasing at a rate of 25 fps. These sensors provide for initiation of the normal mode of engine shutdown (LOX depletion cutoff) for the S-IC stage (Figure 5 and Table 1).

2. Fuel Systems (Figure 6)

a. Fuel Loading and Draining Fuel (RP-1) is loaded aboard the S-IC Stage at T-20 hours 46 minutes from three 8600 gallon ground supply tanks in the following sequence:

1. Initial flow of ground supplied fuel begins at a flow rate of 200 gpm ("slow fill rate") and is fed through the lower bulkhead of the S-IC Fuel Tank until it reaches a level of about 10% of the fuel tank capacity.

2. At this point the flow rate is increased to a maximum rate of 2000 gpm ("fast fill rate") which continues until a fuel level sensor at the top of the tank (99% level) is triggered.

3. At this point slow fill (200 gpm) is resumed until loading is completed (sensing done by the sensor mentioned above) at a propellant level slightly above the required level (about 102%). Replenishment of fuel at a rate of 200 gpm can be performed during the countdown anytime a minor fuel loss occurs prior to the S-IC "level adjust operation."

4. The "level adjust operation" which occurs at approximately twenty minutes prior to launch is used to adjust the fuel from the 102% level to the required mission level by means of control of drainage by the fuel level sensor.

The 216,000 gallon fuel tank (Reference 2) is filled by GSE connected to the S-IC by the Tail Service Mast on the LUT. One six-inch fill and drain line is connected between the Tail Service Mast disconnect and the fuel tank aft bulkhead. This line contains a ground operated pneumatically controlled ball type fill and drain valve and provides the filling and normal fuel draining apparatus for the S-IC stage. The fuel fill and drain valve and the fuel vent and relief valve are kept opened during RP-1 filling and topping operations. Ground supplied gaseous nitrogen is provided via prepressurization lines for purging the tank ullage area and for maintaining a positive tank pressure during the filling and topping operation. Fuel loading is controllable to an accuracy of ±.25% of the desired fuel weight. The RP-1 loading operation described, generally takes in the neighborhood of two hours to complete.

Drainage of the fuel tank is conducted using the same ducting, valves, and fittings as the fuel fill system. The S-IC fuel vent and relief valve and the fill and drain valve previously discussed remain open during the "gravity" drain process. This process has a nominal drain rate of 13,400 lbs/min. A "pressure" draining procedure also can be employed to accelerate this operation. This is done by pressurizing the ullage space of the tank with ground supplied nitrogen and keeping the S-IC vent and relief valve closed while the fill and drain valve is in the opened position. "Pressure draining" enables draining of the tank to be reduced to a 30 minute operation.

An emergency draining system which employs an additional drain line (12 inches in diameter) from the fuel tank aft bulkhead to test stand GSE (containing a ground controlled pneumatically operated emergency drain valve) is used to perform drainage of the fuel tank in about 18 minutes. This system is connected only for test stand operations.

b. Fuel Measurements Two continuous level topping sensors are located at the top of the S-IC fuel tank for RP-1 loading operations. These capacitance type sensors are capable of measuring fuel levels above the 2% ullage level in the tank and are designed to overlap with measurements provided by the S-IC measuring system.

A slosh measurement system incorporating four segmented capacitance gauges near the wall of the fuel tank (at 90° intervals) is installed on early models of the S-IC stage.

Liquid level measurements are provided by a separate liquid level segmented capacitance gauge which is physically attached to the center LOX suction line tunnel in the fuel tank.

Temperature sensors (three sets of three sensors), located at several locations in the tank, have a tolerance band of $\pm 3^{\circ}F$ and are used to provide RP-1 density data to ground systems for fuel loading operations.

c. Fuel Conditioning The requirement for prelaunch RP-1 conditioning has been deleted from the S-IC stage.

d. Fuel Pressurization (Figures 6 and 7, and Table 2) Fuel tank pressurization is required during engine starting and flight to establish a suitable net positive suction head (NPSH) at the fuel inlet to the engine turbopump. The MSFC minimum steady state RP-1 NPSH requirement is 106 ft. of RP-1 (36.9 psia). This value is 25% above the engine manufacturer's established requirement.

Prepressurization of the fuel tank with ground supplied gaseous helium begins at about T-1.5 minutes in the countdown. This helium is introduced into the cold helium line downstream of the flow controller and is circulated through the engine heat exchanger (Figure 3) to the normally hot helium line and then to the helium distributor which is located at the forward apex of the fuel tank. During prepressurization, the fuel vent and relief valve is kept closed. A prepressurization switch located in the fuel tank, which is disabled at liftoff, is employed to control ground helium supply GSE valving. This switch is designed to actuate at 29 psia, closing the ground supply valve, and deactuate at 27.5 psia.

Flight pressurization which is initiated at liftoff is accomplished by utilizing a separate helium storage and distribution system on the S-IC stage. This system consists of four helium storage cylinders mounted in the S-IC LOX tank (Reference 2), a cold gas line from the helium cylinders' manifold to the engine turbine exhaust manifold heat exchangers, and hot gas lines from engine heat exchangers to the fuel tank helium distributor. The cold gas line includes a flow controller assembly which is designed to regulate fuel tank pressurization rates. Pressurization of helium cylinders from the ground supply is accomplished in two steps in the countdown. At about T-6.5 hours they are prepressurized to approximately 1550 ± 40 psia. This is followed by a pressurization sequence commencing at T-4.8 hours, after the cylinders have been sufficiently cooled by LOX loading (to about -280°F), during which the bottles are pressurized to about 3150 psia. A low pressure switch and a high pressure switch which are located in the Intertank Area (near the flow controller assembly) and a temperature sensor located in one of the four cylinders, control the helium fill and dump valve which supplies ground helium to the bottles. The helium flow controller assembly consists of a bank of five solenoid flow control valves which controls the supply of helium to the heat exchangers and maintains the fuel tank ullage pressure between 24.2 and 29.7 psia. Helium flow to the fuel tank is regulated at a flow rate between 2.5 and 3.5 lbs/sec. One of the valves in the Flow Controller Assembly is normally opened to provide fail safe operation of the pressurization system, three normally closed valves are programmed by the IU Launch Vehicle Digital Computer to fulfill the predetermined needs of the fuel tank, and the last (normally closed) is operated by a pressure switch located in the fuel tank to supply helium demands during flight which are above the capacity of the other valves.

A fuel tank vent and relief valve located in the fuel tank is designed to pass helium at a maximum flow rate of 3.5 lbs/sec. During flight, this valve is operated by a relief pressure switch mounted in the forward dome of the fuel tank and set to operate between 29.7 and 31.5 psia. Provisions are made for mechanical relief between 30.0 and 35.0 psia, should electrical functioning of this valve or its controls malfunction.

e. Fuel Delivery Fuel is delivered to the engines via ten 12-inch diameter fuel suction lines (2 per engine) at a flow rate of 1740.2 lbs/sec (per engine). Suction lines are equipped with gimbal and expansion joints to compensate for alignment tolerances, thermal growth and engine gimbaling (Figure 4). PVC compensating joints are installed in the ducts to allow line movement while maintaining constant fluid volume and to minimize pressure loads that are transmitted to the engine turbopump. Each fuel suction line contains a pneumatic piston operated, normally opened, ball-type prevalve which is controlled by nitrogen supplied from the same solenoid control valve (of the Nitrogen Control Pressure System) which operates the LOX prevalves. Fuel prevalves are located at the fuel tank outlets of fuel suction lines and are used for termination of fuel flow to the engines during static test, prelaunch, and flight operations. A recent change to launch vehicle systems permits prevalves (LOX and fuel) to shut only after thrust decay has been sensed. Fuel flow rate in each fuel line is sensed by a turbine type flowmeter which provides flow measurement to S-IC telemetry systems.

A fuel bi-level depletion sensor with redundant sensing elements at each level is flange mounted through the rear bulkhead of the fuel container and is used to provide backup engine cutoff functions for the engine shutdown sequence during flight of the S-IC stage. This sensor is capable of measuring the fuel level to within ±0.10 inches when the fuel level is decreasing in the tank at a maximum rate of 30 in/sec.

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Attachment
Figures 1 thru 7, Tables 1 and 2

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REFERENCES

For further information concerning the performance, interface and operational details of the systems mentioned herein, the following documents should be consulted:

1. TM 65-2032-2 Saturn V Cryogenic Loading Schedules - Case 40 by G. W. Craft, dated September 1, 1965.

2. Memorandum for File - Description of the S-IC Stage Structure - Case 330 by S. H. Levine, dated February 2, 1967.

3. D5-11717 - Design Requirements for S-IC Stage Program Elements (U) by the Boeing Company, revision dated April 15, 1965.

4. D5-13600-1 - S-IC Stage Performance Prediction for the Flight of the Apollo/Saturn 501 Vehicle (U) by The Boeing Company, dated December 9, 1966.

5. CP02S00001101 Revision B - Saturn V/S-IC Contract End Item Detail Specification (Prime Equipment) - Performance, Design and Product Configuration Requirements by MSFC, dated November 1, 1965.

6. D5-12572-1 - "S-IC-501 System Design Analysis Propulsion Mechanical", Revision M by The Boeing Company, dated January 27, 1967.

7. Rocket Propellant and Pressurization Systems, Elliot Ring, Prentice Hall Space Technology Series, 1964.

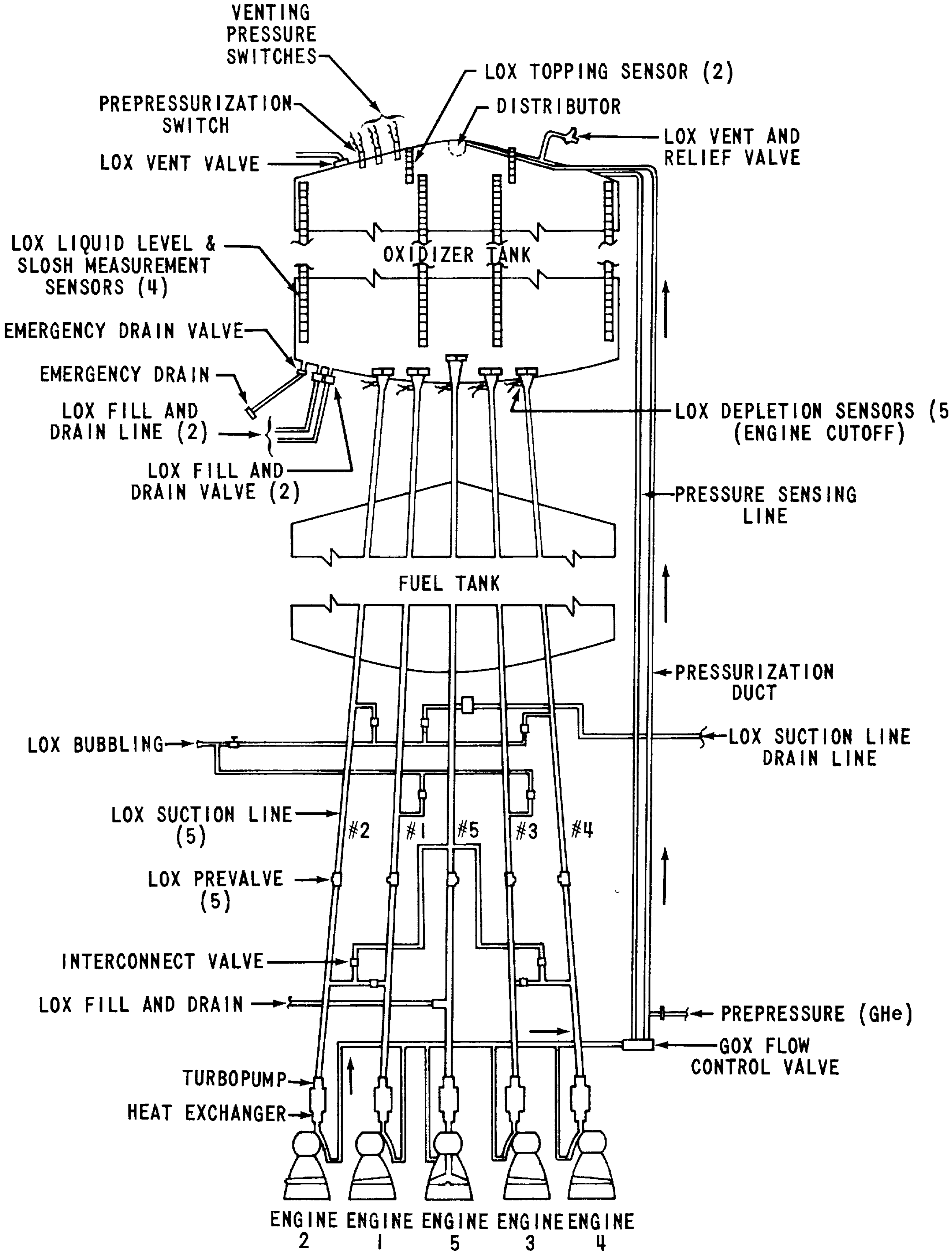


FIGURE 1 - LOX SYSTEM ILLUSTRATION

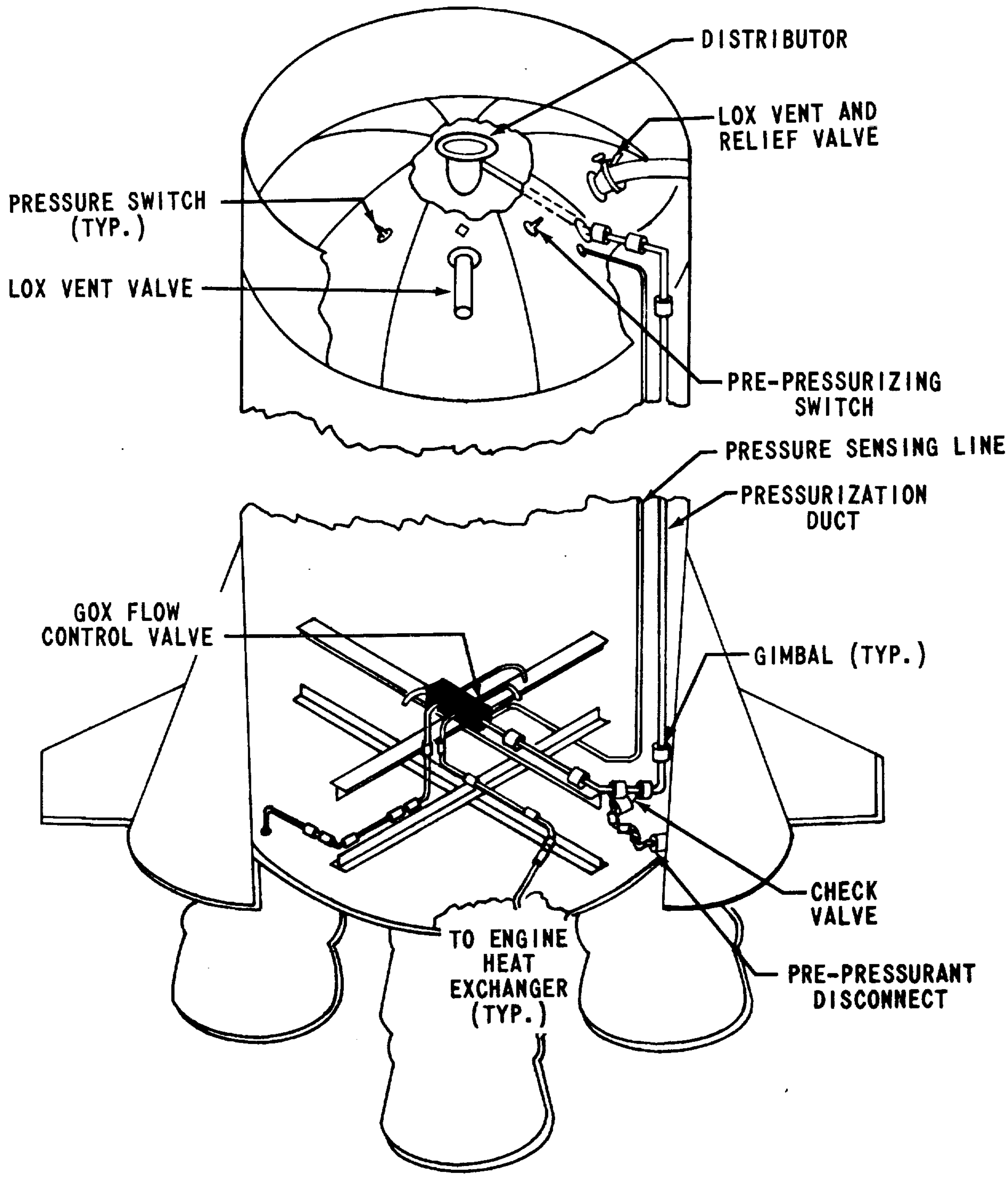


FIGURE 2 - LOX PRESSURIZATION SYSTEM

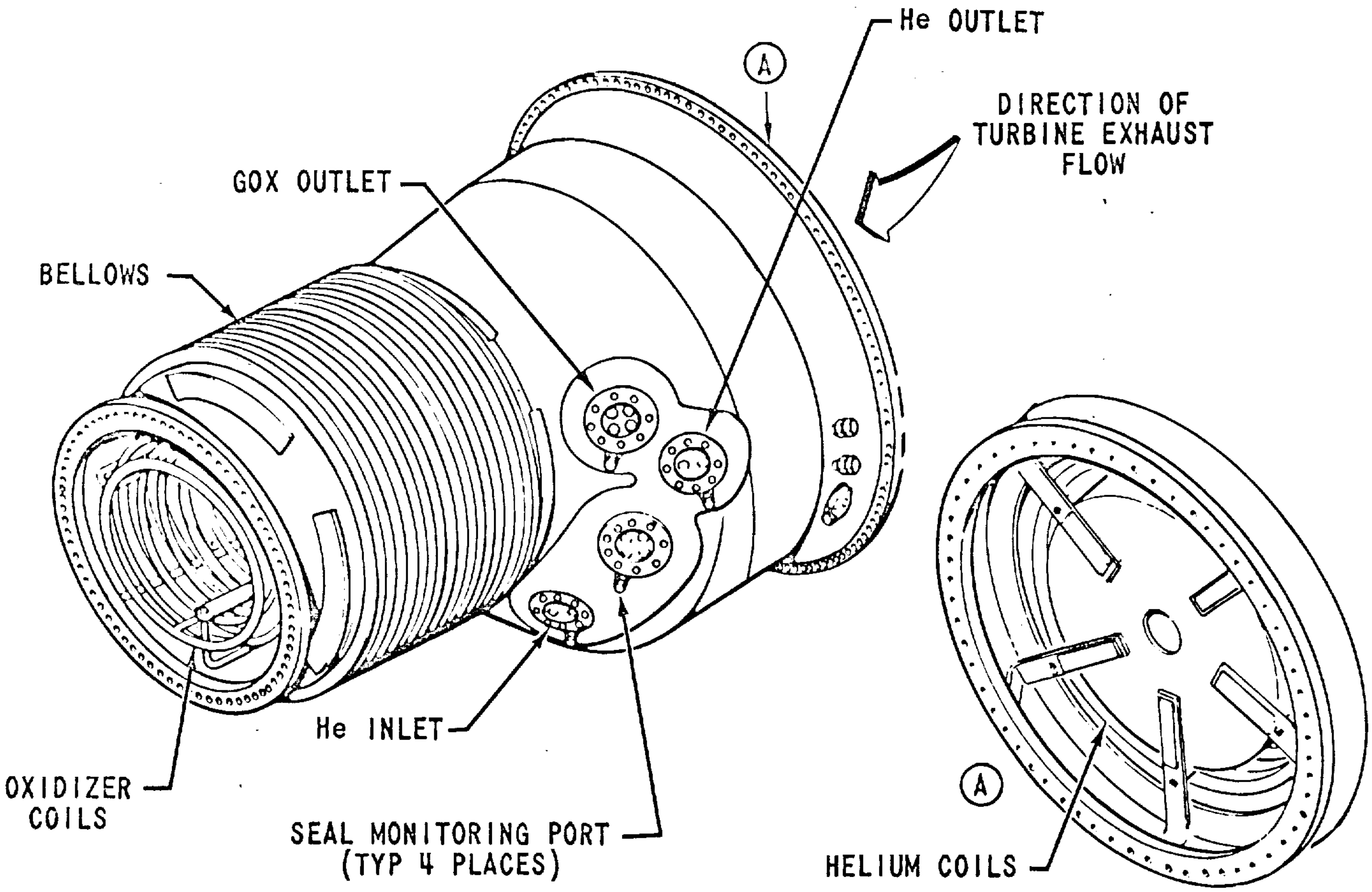


FIGURE 3 - F-I ENGINE
Heat Exchanger

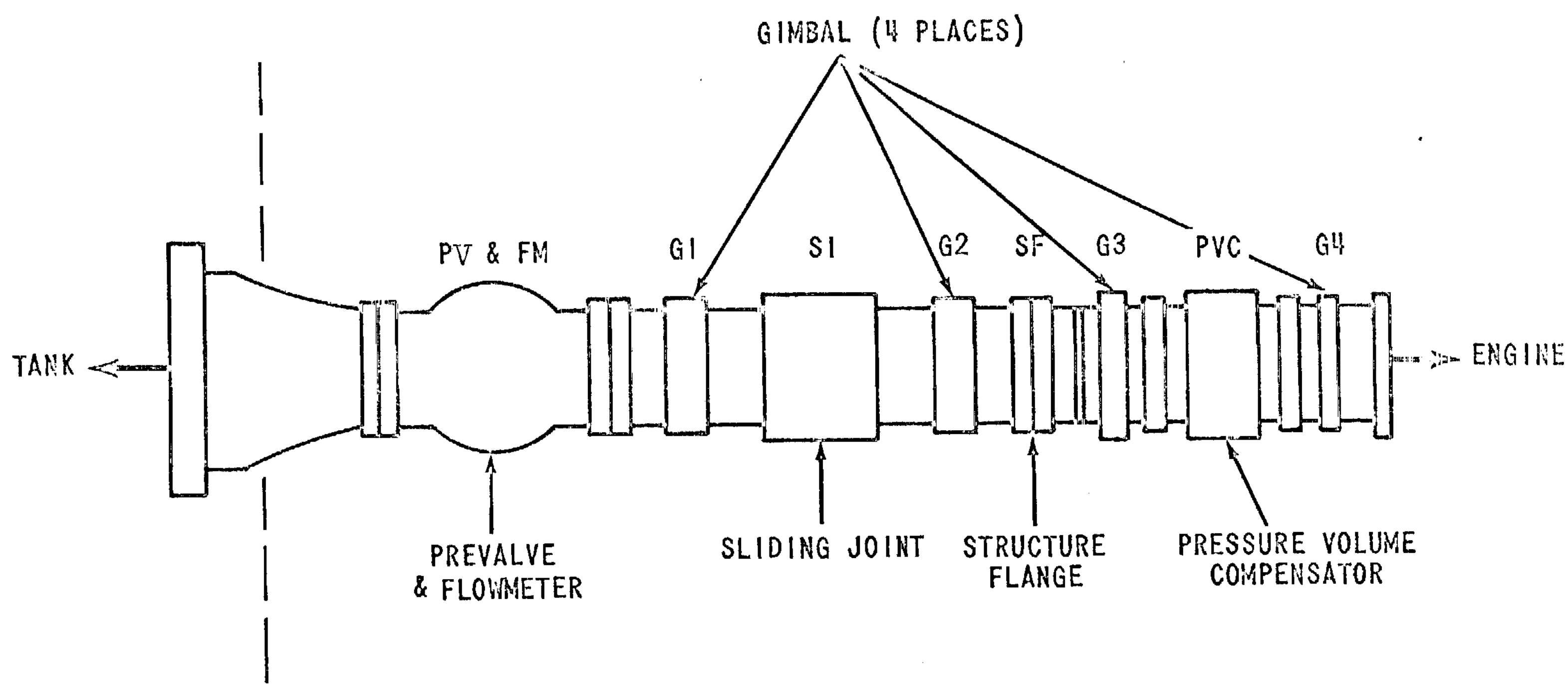
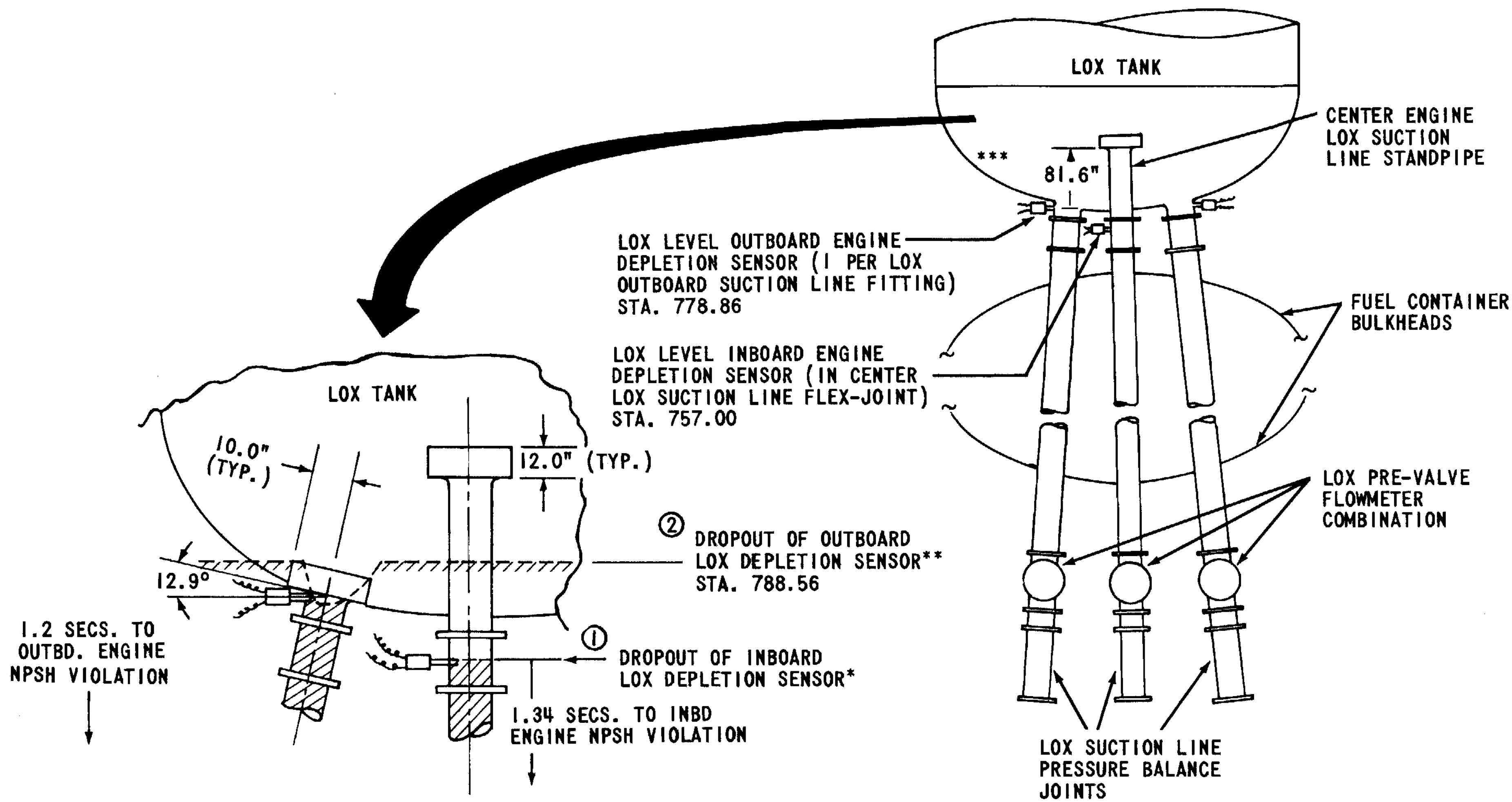


FIGURE 4 - PROPELLANT DELIVERY DUCT (TYP.)



NOTES:

1. THE SYMBOL ////// DENOTES LIQUID LEVEL.
2. * DROPOUT OF DEPLETION SENSOR TRIGGERS TIMER WHICH CUTSOFF INBOARD ENGINE 1.3 SECONDS LATER.
3. ** DROPOUT OF DEPLETION SENSOR(S) TRIGGERS TIMER WHICH CUTSOFF OUTBOARD ENGINE 1.2 SECONDS LATER.
4. *** SEE TABLE 1.
5. S-IC CEI SPEC. CP02S0000110I NORMAL ENGINE CUTOFF REQMTS:
   A. THRUST TERMINATION OF THE CENTER ENGINE WHENEVER LOX LEVEL REACHES A POINT WHERE IT CAN SUPPLY ONLY FOUR ENGINES AT OR ABOVE THE SPECIFIED NPSH FOR AN ADDITIONAL 12 SECONDS (504 AND UP).
   B. THRUST TERMINATION OF OUTBOARD ENGINES WHENEVER THE NPSH CANNOT BE MAINTAINED.

FIGURE 5 - S-IC STAGE NORMAL ENGINE SHUTDOWN - LOX DEPLETION CUTOFF

TABLE I - S-IC STAGE ENGINE CUTOFF MECHANICS

S-IC STAGE	INBOARD ENGINE CUTOFF (IECO) TIME	OUTBOARD ENGINE CUTOFF (OECO) TIME	TIME BETWEEN IECO & OECO	INBOARD LOX SUCTION LINE HEIGHT (LIP TO TANK BOTTOM)
S-IC-1	LIFTOFF + 135.5 SECS. (INBOARD SUCTION LINE FULL AT FLIGHT TERM.)	OUTBOARD DEPLETION SENSOR DROPOUT + 1.2 SECS. TIME DELAY	APPROX. 17 SECS.	48.3 IN.
S-IC-2	INBOARD DEPLETION SENSOR DROPOUT + 1.3 SECS. TIME DELAY	OUTBOARD DEPLETION SENSOR DROPOUT + 1.2 SECS. TIME DELAY	APPROX. 4.9 SECS.	48.3 IN.
S-IC-3	LIFTOFF + 135.5 SECS. (INBOARD SUCTION LINE FULL AT FLIGHT TERM.)	OUTBOARD DEPLETION SENSOR DROPOUT + 1.2 SECS. TIME DELAY	APPROX. 17 SECS.	48.3 IN.
S-IC-4	INBOARD DEPLETION SENSOR DROPOUT + 1.3 SECS. TIME DELAY	OUTBOARD DEPLETION SENSOR DROPOUT + 1.2 SECS. TIME DELAY	APPROX. 12 SECS.	81.6 IN.

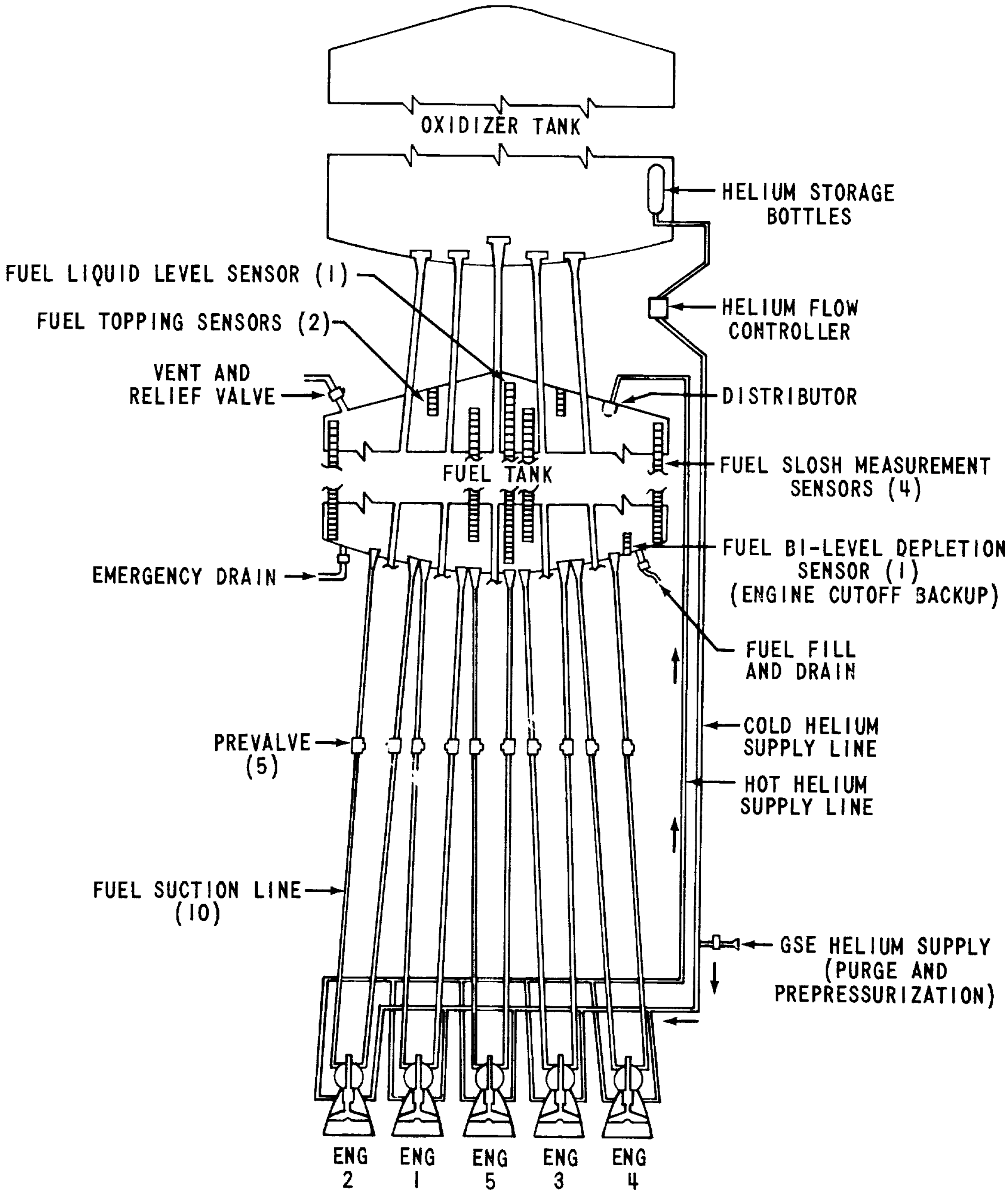


FIGURE 6 - FUEL SYSTEM ILLUSTRATION

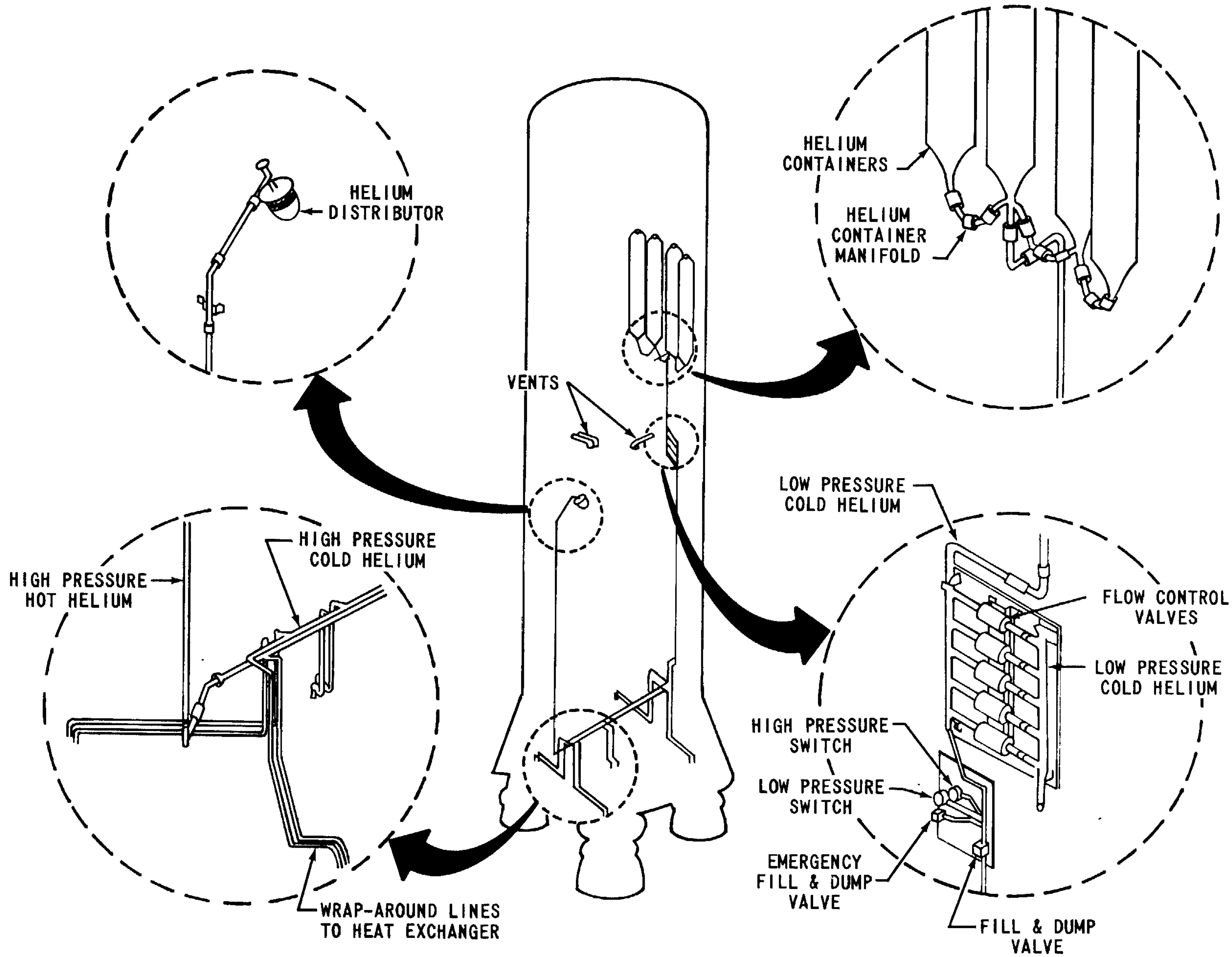


FIGURE 7 - FUEL PRESSURIZATION

TABLE 2

SUMMARY TABLE
S-IC PROPELLANT PRESSURIZATION LIMITS

FUNCTION	LOX SYSTEM	FUEL SYSTEM
1. NPSH REQUIREMENT - ROCKETDYNE	65 FT. (31.9 PSIA)	85 FT. (29.6 PSIA)
2. NPSH REQUIREMENT - MSFC	81 FT. (39.8 PSIA)	106 FT. (36.9 PSIA)
1. PREPRESSURIZATION (GROUND GHe)	26.0 - 24.2 PSIA	27.5 - 29.0 PSIA
2. IN-FLIGHT PRESSURIZATION	18.0 - 20 PSIA (GOX) (GOX FLOW CONTROL VALVE)	24.2 - 29.7 PSIA (GHe) (GHe FLOW CONTROLLER)
1. RELIEF SWITCH SETTINGS	(To T+75 SECS) 29.0-27.5 PSIA (T+65 ON) 25.5-23.7 PSIG	29.7 - 31.5 PSIA
2. MECHANICAL RELIEF VALVE SETTING	24.0 - 25.5 PSIG	30.0 - 35.0 PSIA